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Additive manufacturing of a 4th-order K-band semi-planar slow-wave filter

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***Abstract*—This paper presents the exploitation of the additive manufacturing (AM) technique laser powder bed fusion (L-PBF), for the fabrication of a K-band meta-substrate filter. The decisions made through each round of prototyping are discussed. It also presents the crucial parameters that can lead to a higher quality end product of AM. The filter response and out-of-band performance are also discussed in short.**

***Index Terms*—Additive manufacturing, filter, laser powder bed fusion, miniaturization, selective laser melting, slow-wave.**

I. Introduction

Additive manufacturing is earning its place in the satellite industry because of its ability to produce components at lower cost, size, and weight than conventional manufacturing techniques. Additionally, since it enables rapid prototyping, the possibility to manufacture highly complicated components, and by improving the feasibility of in one-piece fabrication of components, it has gained favor in recent studies [1]. The ever growing demand of higher bandwidth in satellite applications, necessitates the exploitation of ever higher frequencies. These higher frequencies push components to become smaller and so the manufacturing challenges increase. It is therefore necessary for studies to push the boundaries of the AM field to enable methods to meet these growing needs of satellites.

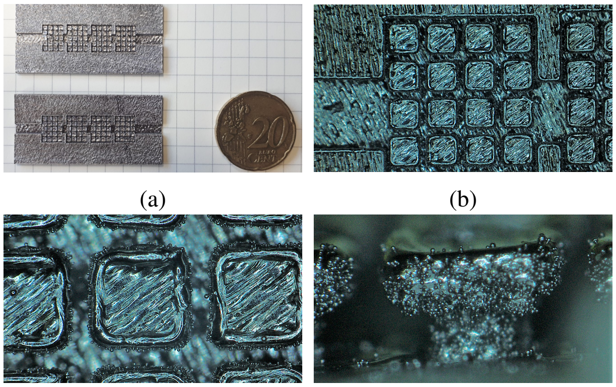
Filters are an essential part of any telecommunication system and provide a relatively simple way to test the performance of a manufacturing technology. The trend in current filter research is to pursue higher performance in terms of loss [2], miniaturization techniques [3], [4], and out-of-band rejection performance [5]. Miniaturization is of key importance for satellite applications, since the size of components directly contributes to the launch costs, and therefore optimisation is desirable. This criteria makes AM an attractive manufacturing technology as one can perform topology optimisation for example to greatly reduce weight.

The exploitation of slow-wave (SW) structures [6] using AM technology gives the ability to meet these requirements. These structures are also referred to as meta-substrate structures in some literature [3]. A slow-wave structure working principle is based on reducing the group velocity of a transmission line. Slow-wave structures provide a high percentage of miniaturization and a relatively good out-of-band rejection. In the course of this work, dielectric losses are removed using an AM implementation, which additionally results in improved performance. The SW structure has implementation challenges when compared to more conventional designs. This provides a good case study of the limits of the used AM technology and an opportunity to develop best practises with design rules for the optimum results.

In a previous work, a semi-planar metasubstrate structure which provided miniaturization and lower-loss, was developed for AM [7]. The paper demonstrated, through simulation, a mushroom meta-substrate K-band filter where an array of periodic mushroom pins (metasubstrate), creates artificial dielectric permittivity. The manufacturing of the prototypes was performed using EOS EOSINT M 280 L-PBF printer. As with any AM technology, L-PBF, also known as selective laser melting (SLM), implicates accuracy limitations which need to be optimized for. This is especially challenging with the shapes and sizes required in the K-band. To overcome this, a possible solution was explored: shape optimization of the unit-cell of metasubstrate for the current L-PBF technology. This paper will detail the challenges encountered through the process, along with the approaches taken for improvement which the readers may use in their own future implementations.

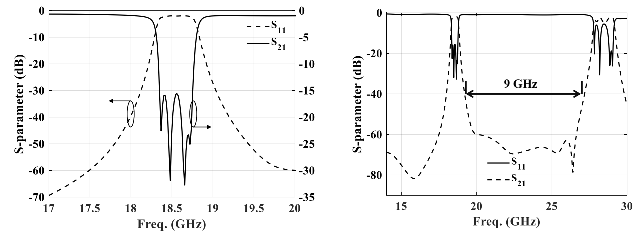
II. Filter developement

The initial investigation of the AM implementation of mushroom metasubstrate is reported in [7]. During the prototyping



(a) (b) (c) (d)

Fig. 1: (a) Mushroom meta-substrate prototype, (b) single resonator, (c) mushroom deformation, (d) mushrooms sidewall view.



(a) (b)

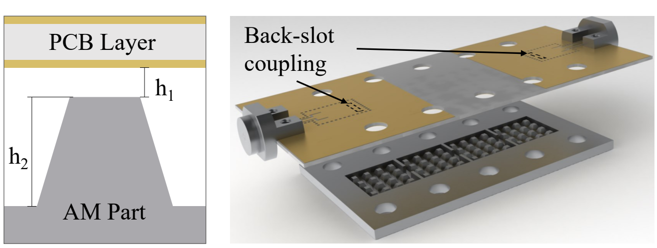
Fig. 3: (a) S-parameter of the filter, (b) out-of-band rejection performance of filter.

process, several iterations were made with adaptations needed to fulfill the design for additive manufacturing (DfAM) rules [8]. The process showed that the initial design was not suitable for the available L-PBF machine, the following subsections detail the necessary optimisations to obtain the desired filter.

A. Unit-cell optimization

The first prototype, discussed in previous work, is shown in Fig. 1a. The surface roughness, especially on top of the pins was harsh, and in some cases deformation of the pins is visible, shown in Fig. 1b and 1c. Additionally, the side walls of the pins were not smooth enough, as shown in Fig. 1d, as the dimensions were too small for a vertical wall. Fig. 1d also shows that the metal powder sticking to these walls changes the shape as well and increases the roughness. Preliminary surface roughness measurements show a surface roughness of 8 to 10 μm. The issues combined lead to the conclusion, that a trade-off needed to be made in terms of the unit-cell shape to improve the printed parts.

The DfAM rules and experience gained with the discussed prototypes led to the conclusion that the meta-substrate must be fabricated with pyramidal pins. This change in shape has the following benefits, when compared to the first design, in terms of printability: First, the previously designed mushrooms have overhangs with small geometries which are unstable during print, if unsupported. A practical solution to overcome this is to apply a 45^o chamfer to the wall. Secondly, since the mushroom cells have a thin overhang, it is not feasible to provide a sufficient quality surface by L-PBF. Third, AM techniques that use materials with poor conductivity (such as titanium) will require the extra step of metalization with high conductive materials such as copper, silver or gold. The mushroom cells have a shadowing effect due to the overhanging walls, making it difficult for coating techniques such as physical vapor deposition (PVD), to provide an adequate coating in these key positions. It is important to note that changing from the mushroom to a pyramidal pin is considered a trade-off in terms of RF performance. The printability comes at the cost of the miniaturization factor when compared to the mushroom-cells [7]. The adapted pyriamidal unit-cell is shown in Fig. 2a, as well as a 4-pole inline filter consisting of these unit-cells in Fig. 2b.



(a) (b)

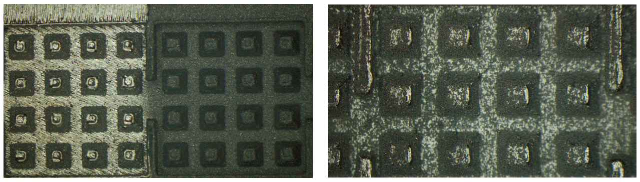
Fig. 2: (a) Pyramidical unit-cell, (b) 4-th order filter.

B. EM performance optimization

The EM performance of the prototype also underwent enhancements during the prototyping process when compared to the first design [7]. The feeding of the filter was improved with the design of a new GCPW-to-SIW-to-metasubstrate transition. The implementation of this new transition improved the level of out-of-band rejection and the insertion loss in general. The improved upper out-of-band rejection is partly a result of using SW structures, which is due to the electromagnetic band-gap nature of this structure, as depicted in Fig. 3b. It also improved the leakage from input to output which improved the unintended transmission zeros in the filter response of the first prototype. The filter was designed in a two layer configuration, where the meta-substrate is fed through a back-slot coupling from a SIW to the meta-substrate. This setup makes the designed filter a surface mountable component.

C. SLM process optimization

During the prototyping, the process was iteratively improved with several optimization methods to enhance the final product. The optimization parameters were DfAM implementation, build orientation, and process parameters. The main takeaway from DfAM rules was that the layer thickness and the wall thickness, in particular areas such as thin walls (in the design phase), must be set to a minimum thickness based on the



(a) (b)

Fig. 4: (a) Horizontal orientation build, right half sand-blasted, (b) 45° tilted orientation build with unmelted sticking powder.

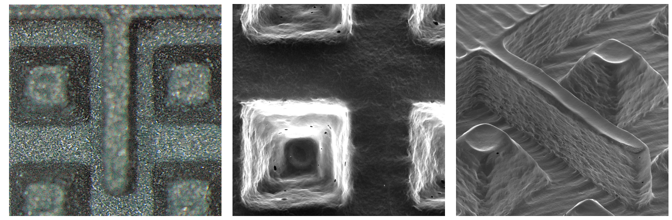
AM device in use. This provides a lower surface roughness in the final part. Build orientation is also critical in the design, as components built in a horizontal orientation are more susceptible to warpage during fabrication than those with a tilted orientation. Components fabricated in tilted orientation, however, have a more jagged surface due to the staircase effect and unmelted powder sticking to the surface. A comparison of the two surfaces produced in the different orientations is shown in Fig. 4a and Fig. 4b. The sets of contour parameters for up- and down-skin (consisting of laser power and laser speed) are the process parameters that need to be optimized and require some study to achieve a better final product's surface roughness. Optimizing these parameters and using other surface roughness reduction techniques such as sandblasting resulted in high-quality surface roughness on the prototypes. The surface roughness achieved after implementing these optimization steps was in the order of 4 to 5 μm, which is half that of the first prototypes.

D. Surface post-treatment

To further improve the surface roughness, a series of post-processing steps called Hirtisation® have been applied, which resulted in an even smoother surface roughness in the order of 2.5 to 3.5 $\mu\mathrm{m}$. The results of sandblasting and Hirtisation® are shown in Fig. 5a and 5b, respectively. Hirtisation is a commercialized process offered by RENA Technologies Austria (formerly Hirtenberger Engineered Surfaces GmbH). It is important to mention that while post-processing procedures, such as sandblasting, generally help with the peak-to-valley surface roughness reduction, other processes such as Hirtisation mainly help with average surface roughness reduction.

E. Metalization

The conductivity of the AM final part is an important contributor to the losses, and the PVD is one of the solutions that can provides an exceptional result for the metalization of the prototype. This is attributed to PVD providing a dense coating, with its conductivity close to that of silver. Additionally, The PVD coating itself does not introduce a noticeable increase in surface roughness, compared to that of the original part, and therefore can provide a high quality conductive coating. To illustrate the difference, a samples of the metasubstrate was coated with 8 μm of silver using PVD, shown in Fig. 5c. The surface roughness was not affected by the PVD coating,



(a) (b) (c)

Fig. 5: Surface detail (a) after sandblasting, (b) after hirtisation and (c) after PVD process.

with the overall surface roughness measured at between 2.5 to 3.5 $\mu\mathrm{m}$.

III. Conclusion

A series of techniques for improving the SLM process and post-treatment for the fabrication of components suitable for RF and microwave applications was presented. The optimization process helped reduce the surface roughness of the final prototype to one third of the initial prototype. Additionally, the improved feeding helped achieve a better EM performance and reduce the losses.

IV. Acknowledgement

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